

Beam-dust interactions in an e^+e^- collider

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In recent electron-positron colliders designed and operated with very low emittance and high current, the energy density of the beam has increased significantly compared to earlier designs. Under these conditions, interactions between the beam and residual materials within the beam pipe exert considerable mutual influence. The residual materials are heated by the beam, leading to evaporation, charging, and possible fission, eventually resulting in a plasma state. Conversely, the beam undergoes emittance growth due to electromagnetic interactions with the resulting plasma. We investigate the effects of such dust-induced plasma on the beam through numerical simulations of these processes.

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I. INTRODUCTION

The effects of dust on beams were initially observed in electron storage rings used as synchrotron radiation sources [1–5]. In recent years, dust-related effects have also been detected in proton beams at the Large Hadron Collider, manifested as unidentified falling object events [6–11]. More recently, sudden beam losses (SBL) have been observed primarily in the positron ring (LER) of SuperKEKB, which are suspected to be caused by dust.

The beam losses in SuperKEKB occur within a very short time span of a few turns ($10 \sim 50 \mu\text{s}$). In some instances, such losses have induced quenches in superconducting magnets near the collision point. This phenomenon represents one of the most critical issues in achieving higher beam currents. The characteristics of the beam loss can be summarized as follows: (i) In most cases, it occurs under high beam current conditions of over 500 mA. (ii) The beam loss begins abruptly without any precursor of dipole oscillation and leads to an abort within one to several turns. (iii) It occurs independently of beam-beam collisions. (iv) It is more frequent in the 4 GeV low energy positron ring (LER) but also occurs in the 7 GeV high energy electron ring (HER).

In the collider, collimators are positioned as closely as possible to protect the detector and minimize background noise. For SuperKEKB, with a vertical emittance of $\varepsilon_y = 5 \times 10^{-11} \text{ m}$ [12], the physical aperture is

$2J_{y,\text{max}} = 0.8 \times 10^{-7} \text{ m}$ [13], corresponding to $40 \sigma_y$. This implies that positrons in the beam can exceed this amplitude within a few turns even in the absence of coherent dipole oscillations.

To investigate the cause, extensive experiments were conducted at the SuperKEKB accelerator [14]. Beam aborts were intentionally triggered by physically striking the beam pipe in the wiggler section. Initial hypotheses considered copper (from the beam pipe) and silicon (from VACSEAL, a material commonly used for vacuum sealing repairs) as potential atomic gas sources. Simulations of beam-dust interactions based on copper and silicon dust were presented in Ref. [15]. Upon inspection of the beam pipe, particles several tens of micrometers in size were observed, and compositional analysis identified them as graphite. This graphite is thought to be organic matter that has been carbonized by irradiation with synchrotron radiation.

The beam size immediately after the abort was measured turn-by-turn using a gated camera and a streak camera. An increase in the vertical beam size was observed at the occurrence of SBL [16].

In this paper, we discuss the interaction between a positron beam and graphite dust by means of simulation. Graphite sublimates directly from a solid to a gas at approximately 3500 K; no liquid phase exists under the vacuum conditions of the beam pipe. The beam-dust interaction model was subsequently improved to include the absorption of ionization-generated electrons onto dust surfaces and subsequent secondary electron emission. Furthermore, the use of graphite, a sublimating material, introduces a qualitatively distinct physical regime.

Initially, simulations were performed under the assumption that vacuum bumps were the cause of beam aborts. These simulations revealed that when approximately

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10^{10} ions are generated near the beam, the beam experiences strong defocusing, resulting in amplitudes large enough to induce beam loss. This type of loss stems from an instantaneous mismatch in the Twiss parameters, implying that dipole oscillations are not necessarily observed. This mechanism is discussed in Sec. II.

The fundamental physical properties of dust particles under beam irradiation are examined in Sec. III. The simulation accounts for beam ionization loss in a dust, electron production, electron absorption, secondary electron emission, evaporation, and ionization of atomic gas. Charged particles, including the beam and ionized atomic gases, are represented as macroparticles, and their motion is tracked within the electric field generated by the ensemble using the particle-in-cell (PIC) method [17,18]. Building on these physical principles, the simulation of beam-dust interactions is presented in Sec. IV.

The SBL phenomenon in SuperKEKB is observed on the timescale of several turns. Conducting a multiturn simulation involving all bunches is computationally challenging due to resource limitations. Therefore, a simplified model was used to perform a multiturn simulation, as described in Sec. V.

II. INTERACTION BETWEEN RESIDUAL GAS AND THE BEAM

We begin by examining the case of a sudden pressure bump. Similar approaches have been employed in studies of electron cloud instability [19,20] and ion instability [21], making this method a suitable initial step for understanding the overall phenomenon. Assuming a pressure of $P = 2$ Pa at a temperature $T = 300$ K or $P = 20$ Pa at $T = 3000$ K within a region of $l_z = 1$ m, we evaluated its effect on the beam. The gas is assumed to be composed of carbon, which has an atomic number $Z_i = 6$ and a mass number $A_i = 12$. The corresponding integrated density over a length 1 m is $\rho_G = 5.3 \times 10^{20} \text{ m}^{-2}$.

The effect of beam collisions with residual gas molecules in the beam pipe is a fundamental and critical concern in accelerator design and operation, and extensive research has been conducted on this topic. From the perspective of beam lifetime in GeV-class electron and positron beams, Coulomb scattering with atoms, which significantly alters the transverse momentum of beam particles, and bremsstrahlung, which substantially changes their energy, are dominant effects and are routinely evaluated during the design phase.

Residual gas is neutral, so its interaction with the beam is primarily characterized by Coulomb scattering. The cross section for Coulomb scattering is given by

$$\sigma_{\text{Coul}} = \frac{4\pi r_e^2 Z_i(Z_i + 1)}{\gamma^2 \theta_c^2}, \quad (1)$$

where γ is the relativistic factor, r_e is the classical electron radius, and θ_c is the minimum angular spread that leads to

beam loss, defined as

$$\frac{1}{\theta_c^2} = \frac{\beta_x}{4J_{x,\text{max}}} + \frac{\beta_y}{4J_{y,\text{max}}}. \quad (2)$$

Here, $2J_{x,\text{max}}$ and $2J_{y,\text{max}}$ represent the transverse acceptance in terms of action variables, and $\beta_{x,y}$ denotes the beta function at the location where Coulomb scattering occurs. The beam loss rate per collision is given by

$$\frac{T_0}{\tau} = \frac{Pl_z}{k_B T} \sigma_{\text{Coul}}, \quad (3)$$

where k_B is the Boltzmann constant, τ the lifetime, and T_0 the revolution time.

In general, for high-energy electrons, energy loss due to bremsstrahlung, which causes particles to be lost outside the energy aperture, is also significant. However, in the case of SuperKEKB, the transverse aperture is constrained by collimators, making Coulomb scattering the dominant loss mechanism [13]. For graphite ($Z_i = 6$) at $T = 300$ K and $Pl_z = 2$ Pa m, the lifetime is calculated to be 1.1 s (1.1×10^5 turns), independent of beam current and emittance.

Next, we consider the scenario in which the gas becomes ionized. Using the integrated gas density $\rho_G = 5.3 \times 10^{20} \text{ m}^{-2}$ and assuming an ionization cross section of $\sigma_{\text{ion}} = 2 \times 10^{-22} \text{ m}^{-2}$, the number of ions produced per bunch passage (with $N_p = 6.25 \times 10^{10}$ particles) is $\Delta n_i = 6.6 \times 10^9$, corresponding to a density increment of $\Delta \rho_i = 2.0 \times 10^{17} \text{ m}^{-2}$. Electrons are generated simultaneously in equal numbers. The positron beam focuses electrons and defocuses ions, while it is itself focused by electrons and defocused by ions. Since the spatial distributions of electrons and ions differ, their effects do not cancel, leading to net changes in beam dynamics.

As the bunch train traverses the region, electron and ion clouds are formed. Each bunch interacts with the electron or ion cloud, altering its motion. To simulate the generation of electron/ion clouds and their interaction with bunches, each bunch of length $\sigma_z = 6$ mm is divided into 40 slices along the direction of propagation. Whenever a bunch passes through the gas, macroparticles representing electrons and ions are generated. The electrostatic potentials of both the electron/ion clouds and each bunch slice are computed using the particle-in-cell (PIC) method, and their mutual interactions and motions are tracked. The number of macroparticles is fixed at 10^6 for the positron bunch, while it varies between 10^5 and 10^6 for ions and electrons.

The beam emittance of SuperKEKB is $\epsilon_x = 4$ nm and $\epsilon_y = 50$ pm, with average beta functions $\beta_x = \beta_y = 10$ m in both planes. The beam sizes are $\sigma_x = 200$ μm and $\sigma_y = 22$ μm . The electron plasma frequency is

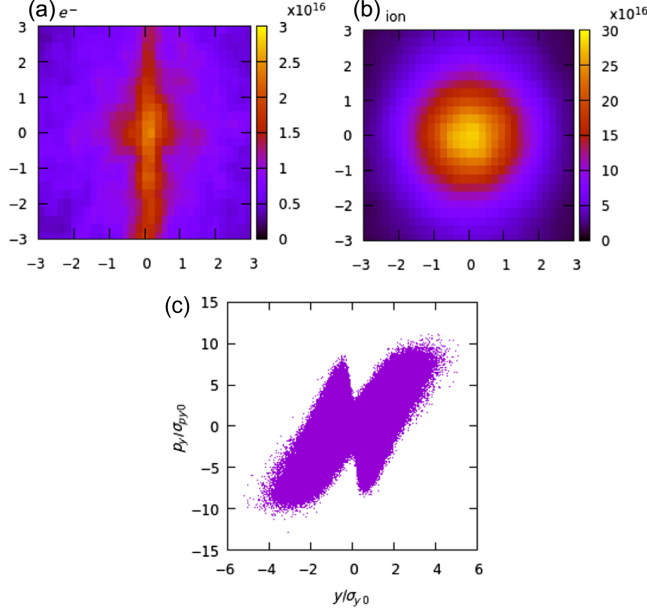


FIG. 1. Distribution of electrons, ions, and beam particles after 10 bunch passages. Plots (a) and (b) display the electron and ion distributions, respectively. Plot (c) displays the vertical phase-space distribution of the beam particles in the 10th bunch. The horizontal and vertical axes represent x/σ_x and y/σ_y , respectively. The color scale in (a) and (b) represents density in units of m^{-2} .

$$\omega_e = \left(\frac{N_p r_e c^2}{\sqrt{2\pi\sigma_z\sigma_x\sigma_y}} \right)^{1/2} = 2\pi \times 90 \text{ GHz},$$

and the number of slices per bunch (40) exceeds $\omega_e \sigma_z / c \approx 9.4$. The bunches pass through the gas every 4 ns.

Figure 1 shows the distributions of electrons, ions, and beam particles after 10 bunch passages. Plots (a) and (b) depict the electron and ion distributions, respectively. The horizontal and vertical axes represent x/σ_x and y/σ_y , where $\sigma_{x,y}$ denotes the beam size. Plot (c) shows the vertical phase-space distribution of the beam particles in the 10th bunch.

Near the center, the bunch is focused due to the electron cloud. Overall, however, the bunch experiences defocusing caused by the ion cloud. From the slope of the phase-space distribution, it can be inferred that the focusing component, though narrow in range, is several times stronger than the defocusing component. Plot (a) shows the electron distribution after bunch passage; however, it is reasonable to assume that during bunch passage, the electron distribution is more highly localized than that of ions. The defocusing strength is estimated as $K\beta_y \approx 5$. This value is relatively large, corresponding to a tune shift of approximately 0.4, but it is not sufficient to cause sudden beam loss.

We investigate the multiturn effects of beam interactions with residual gas. The ion distribution saturates around the

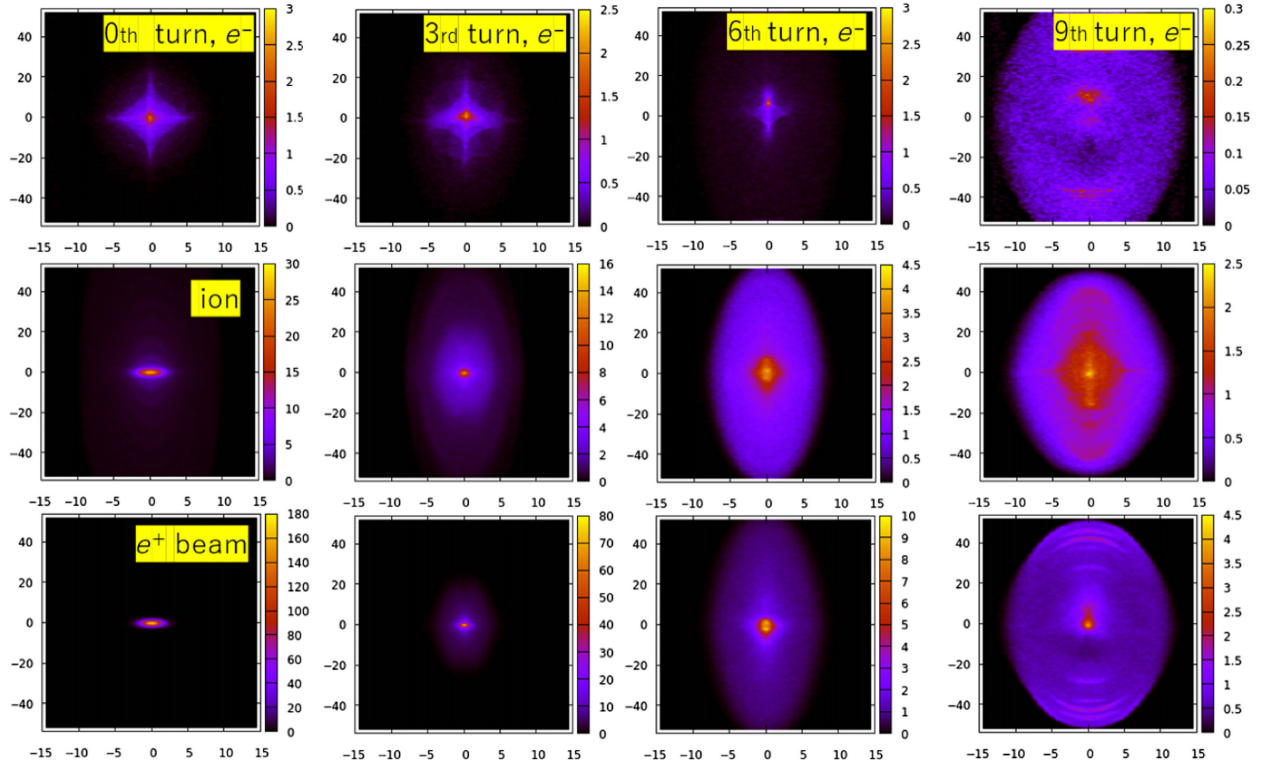


FIG. 2. Electron, ion, and beam distributions during the interaction with the 10th bunch after 0, 3, 6, and 9 turns. The color scale represents density in units of 10^{16} m^{-2} .

10th bunch passage. Subsequently, the bunch interacts with this saturated distribution over multiple turns. Figure 2 shows the electron, ion, and beam distributions for the 10th bunch after several turns (as indicated in the figure). The beam distribution expands to $\approx 50\sigma_y$ by the 4th turn. This size is sufficient to cause beam loss.

A similar simulation has been conducted for copper (mass number $A_i = 64$) in Ref. [15]. For graphite with mass number $A_i = 12$, the phase-space distribution of beam particles exhibits a relatively clear focusing component, as observed in Fig. 1. In the beam distribution shown in Fig. 2, the core portion remains more distinct for graphite compared to copper.

III. INTERACTION BETWEEN DUST AND THE BEAM

In this section, we review the formalism for beam-dust interactions. Based on this framework, simulations of interactions between the beam and dust in the plasma state will be presented in the following section. We consider a spherical dust particle of radius a located at the center of the beam. Prior to the main analysis, we first estimate the beam lifetime resulting from Coulomb scattering on the dust particle. The loss rate per collision is given by

$$\frac{T_0}{\tau} = \frac{4N_A a}{3A_i/\rho} I_G \sigma_{\text{Coul}}, \quad (4)$$

where $N_A = 6.02 \times 10^{23}$ is the Avogadro constant and ρ is the mass density. I_G represents the fraction of the beam intensity that impacts the dust particle, defined by the integral

$$I_G = \frac{1}{2\pi\sigma_x\sigma_y} \int_{x^2+y^2 < a^2} e^{-x^2/2\sigma_x^2 - y^2/2\sigma_y^2} dx dy, \quad (5)$$

where x and y denote transverse coordinates, and σ_x and σ_y are the rms beam sizes. $4a/3$ is the average path length of a beam particle traversing a spherical dust grain of radius a . For graphite (C, $Z_i = 6, A_i = 12, \rho = 1.8 \text{ g/cm}^3$) dust particle with $a = 50 \text{ }\mu\text{m}$, the loss rate is calculated to be 0.06, corresponding to a beam lifetime of 35 turns.

We now examine the ionization of dust by the beam and the subsequent interaction between the charged dust, electron-ion clouds, and the beam. The behavior of dust under beam interaction has been studied in Refs. [2,22]. However, modern beams exhibit significantly smaller emittance and higher intensity than those in earlier studies, necessitating investigation of rapid dynamics in beam-dust interactions.

The average energy deposited in the dust per impacting positron is

$$\Delta E_T = \Delta E_Q \log\left(\frac{\epsilon_{\text{max}}}{\epsilon_{\text{min}}}\right), \quad (6)$$

where

$$\Delta E_Q = 2\pi r_e^2 m_e c^2 N_A \frac{Z_i}{A_i} \frac{4a}{3} \rho. \quad (7)$$

Here, ϵ_{max} and ϵ_{min} are the maximum and minimum energy losses of recoiled (ionized) electrons in the dust, respectively. They are given by

$$\epsilon_{\text{max}} = \frac{Qe^2}{a} + \epsilon(a) + \epsilon_{\text{min}}, \quad (8)$$

where Q is the dust charge in units of electron charge. ϵ_{max} is the energy of an electron that, after traveling a range a , fails to escape the electrostatic potential of the dust particle. $\epsilon_{\text{min}} = (\hbar\omega_p)^2/(2m_e c^2)$ is adopted from Ref. [2] as a characteristic plasmon energy, where $\hbar\omega_p = 28.816\sqrt{Z_i\rho/A_i} [\text{eV}]$ (with ρ given in g/cm^3). In our case, this value is $\epsilon_{\text{min}} = 0.7 \times 10^{-3} \text{ eV}$. The energy loss while traveling a range a is denoted by $\epsilon(a) [\text{eV}]$ and is determined by the relation: $a(\epsilon) [\text{cm}] = 0.823\epsilon^{1.156-0.0954\ln(\epsilon)}/\rho$.

Accounting for beam particle density, the deposited energy becomes:

$$\Delta E_i = \Delta E_T N_p I_G. \quad (9)$$

The charge emitted by the dust is evaluated by the cross section for beam energy loss larger than ϵ_{max} :

$$\Delta Q = \frac{\Delta E_Q N_p}{\epsilon_{\text{max}}} I_G. \quad (10)$$

The temperature rise due to energy deposition ΔE_i is governed by the heat capacity C_T and volume:

$$\Delta T = \Delta E_i \left(\frac{3A_i}{4\pi a^3 C_T \rho} \right). \quad (11)$$

The heat capacity of graphite is 8.5 J/(mol K) at room temperature and increases with rising temperature, reaching $C_T \rightarrow 3N_A k_B = 25 \text{ J/(mol K)}$ above the Debye temperature $\Theta = 2230 \text{ K}$. The same applies to silicon, but its Debye temperature is 645 K .

Liquefaction occurs when the dust temperature exceeds its melting point. If the charge exceeds the threshold, the liquefied dust undergoes fission,

$$Q_{\text{th}} = \sqrt{\frac{16\pi\gamma_s a^3}{r_e m_e c^2}}, \quad (12)$$

where γ_s is the surface tension. Regarding the graphite handled here, the liquid state does not exist, so there is no need to consider fission. Silicon liquefies at 1983 K , so fission must be taken into account.

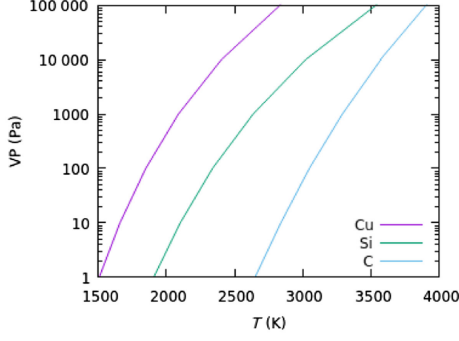


FIG. 3. Vapor pressure for copper, silicon, and carbon graphite [23].

Evaporation becomes significant when temperatures approach sublimation/melting points, driven by vapor pressure $P(T)$. Vapor pressures for Cu, Si, and carbon graphite are shown in Fig. 3.

The number of atom A in the dust decreases as

$$\frac{dA}{dt} = -\frac{4\pi c a^2}{\sqrt{2\pi k_B T M_i c^2}} P(T), \quad (13)$$

where $M_i = A_i M_{AU}$ is the atomic mass.

Vaporized molecules are ionized by beam collisions, producing electrons. The dust transitions to a plasma state comprising charged dusts, ions, and electrons, through which the bunch train propagates while sustaining plasma generation.

Ions are also produced by evaporation from the charged dust, an effect that reduces the net charge on the dust particle. The resulting change in the dust's charge is described by the following equation:

$$\frac{dQ}{dt} = -\frac{2(2\pi a k_B T)^2 M_i}{(2\pi \hbar)^3} e^{-[I-W+V-\sqrt{Q}e^2/a]/(k_B T)+\Delta C_T/k_B}, \quad (14)$$

where

$$\Delta C_T = \int_0^T \frac{d\tau}{\tau^2} \int_0^\tau C_T(T') dT'. \quad (15)$$

Here I is the ionization energy, V is the vaporization energy, and W is the work function. The values $(I, V, W) = (11.3, 7.4, 5.0)$ eV for graphite and $(8.1, 3.1, 4.7)$ eV for silicon are used.

For positron beams, the plasma cloud exerts defocusing forces via charged dust particles/ions and focusing forces via electrons. As these components exhibit distinct spatial distributions, their net effect on the beam does not cancel.

IV. SIMULATION FOR INTERACTION OF BEAM AND DUST PARTICLES

A. Simulation method

We perform a numerical simulation that tracks the state of the dust and the motion of beam, using the formalisms described in Sec. III. The charge distributions of the beam and the dust plasma are represented using the particle-in-cell (PIC) method in the two-dimensional transverse plane. The code is based on that used for beam-beam (BBSS) and electron cloud instability (PEHTS) simulations [17,18]. Their respective electric fields are computed by solving the two-dimensional Poisson equation, and the motion of particles in the beam (positrons) and the dust plasma (ions and electrons) is simulated under the influence of these fields. A positron bunch is represented by 1 million macroparticles. The number of macroions and macroelectrons fluctuates, but their charges are adjusted to maintain a population of approximately 100 000 macroparticles each. The dust is modeled as a discrete particle with defined charge and size.

The initial longitudinal extent of the plasma in the simulation is on the order of the dust size. At this stage, it is comparable to the beam size, making a purely two-dimensional approximation less suitable. However, as the interaction with the beam proceeds, a significant portion of the ions and electrons surrounding the beam originate from previous bunches. These electrons with a thermal velocity of 2.1×10^5 m/s spread over ± 0.9 mm in a bunch interval of 4 ns. Ions and atoms, which move at 1400 m/s ($T = 3000$ K), spread over ± 0.6 mm in 100 bunch passages (400 ns). Since the electrons and ions condensing around the beam are the primary focus, the two-dimensional approximation is considered appropriate.

A graphite dust particle with a radius of 20 or 50 μm is placed at the transverse beam center. The assumption of placing the dust at the beam center seems to be unrealistic; therefore, cases with shifted dust positions will be discussed later. Bunches with a charge of $N_p = 6.25 \times 10^{10}$ pass every $t_{\text{rep}} = 4$ ns. The dust is heated through ionization losses as described by Eqs. (6)–(9) and becomes charged via electron emission according to Eq. (10). Using Eq. (11), the temperature rise due to ionization loss is initially about ~ 40 K per bunch passage, but the rate of increase slows as the temperature rises, owing to the growing heat capacity. The electron energy for which the range equals the dust radius $a = 20$ or 50 μm is $\varepsilon(a) = 48$ or 79 keV, respectively. Approximately 1.9×10^7 or 1.2×10^8 electrons are emitted per bunch passage according to Eq. (10), simultaneously charging the dust to an equivalent positive charge. The number of electrons emitted per bunch passage will go down once the dust is charging up.

In Ref. [15], the interaction between a silicon dust particle and the beam was investigated. The effect on

the beam became noticeable by the 200th bunch and gradually diminished with subsequent bunches. We will discuss simulations related to silicon dust at the end of this section.

Sudden beam loss (SBL) at SuperKEKB, characterized by beam loss occurring over a few turns ($10 \sim 50 \mu\text{s}$), exhibits a significantly longer timescale than the 200 bunches ($0.8 \mu\text{s}$) observed in the simulation. The initial pressure bump scenario in Sec. II aligns more closely with the observed SBL timescale.

In this study, we consider graphite as the dust material, which undergoes sublimation without liquefaction. The simulation was improved to better reflect physical realism by incorporating electron emission, absorption, and secondary electron emission. Emitted electrons oscillate within the beam potential, with most being reabsorbed upon collision with the dust, subsequently triggering secondary electron emission. Simulations were conducted for dust located in both drift space and under a bending field ($B_y = 1 \text{ T}$). A simplified secondary emission model was employed, where the secondary emission yield is set to 0.5 for incident electron energies below 50 eV and 1.0 for energies $\geq 50 \text{ eV}$.

The bunch, with a total length of $6\sigma_z = 36 \text{ mm}$, is divided into 40–120 slices, where $\omega_e \sigma_z / c = 9.4$. The time step for integrating particle motion is $ct_{\text{step}} = 0.9\text{--}0.3 \text{ mm}$. The plasma density created by the beam is very high. In the early stage of the interaction, a dust particle and $\sim 10^8$ electrons are localized within a region of $a = 50 \mu\text{m}$, resulting in a density of $2 \times 10^{20} \text{ m}^{-3}$. This yields an electron plasma frequency of $\omega_p = \sqrt{4\pi r_e n_e c^2} = 2\pi \times 127 \text{ GHz}$, $\omega_p \sigma_z / c = 16$. As shown later, the density can reach 10^{21} m^{-3} as the interaction progresses, resulting in $\omega_p = 2\pi \times 284 \text{ GHz}$, $\omega_p \sigma_z / c = 36$. The frequency is higher than the electron oscillation frequency in the beam potential, ω_e .

The rapid nature of plasma oscillations makes simulations particularly complex. The bunch gap after the beam passage has a length of $ct_{\text{rep}} = 1.2 \text{ m}$. The motion of electrons and ions during this interval is also of interest. However, a preliminary evaluation suggests that plasma oscillations within the bunch gap can likely be neglected. Therefore, it should be sufficient to focus on interactions between the bunch and the dust plasma during their direct interaction. Since it is not yet possible to draw definitive conclusions, this paper will limit its scope to the interaction between the beam and the dust plasma. Interactions within the dust plasma itself, including plasma oscillations, will be addressed in future work.

During the bunch spacing, no beam force is present. In the early stage, where only dust and electrons exist, all emitted electrons with energies below the dust's potential energy are reabsorbed. Secondary electron emission is suppressed during the bunch spacing simulation when

the dust's potential energy exceeds 10 eV (the characteristic energy for secondary emission).

As the dust temperature approaches or exceeds its sublimation point, evaporation intensifies. The dust evaporates as neutral atoms or occasionally as ions, with the rate given by Eqs. (13) and (14). While the model does not account for internal temperature gradients, evaporation is assumed to originate from the beam-irradiated (and thus hottest) region of the dust particle. The evaporated atoms are ionized by the beam, and the resulting electrons are absorbed by the dust during their movement, potentially inducing secondary electron emission. The simulation tracks these processes—generation, motion, and absorption—using macroparticles and macrocharges.

B. Simulation results for graphite dust

Figure 4 shows the evolution of the dust temperature and size. The dust temperature increases by an average of 20 K per bunch passage and reaches the sublimation point ($T = 3500 \text{ K}$) by the 130 ($a_0 = 20 \mu\text{m}$)–190th ($50 \mu\text{m}$) bunch. It then rises further to an equilibrium temperature of 4600–4700 K, where the beam-induced heating balances the heat of sublimation. The dust size gradually decreases due to evaporation as sublimation becomes active, with a reduction rate of $a/a_0 = 2.7 - 1.7 \times 10^{-4}/\text{bunch}$, where $a_0 = 20\text{--}50 \mu\text{m}$, respectively. The temperature saturates at the 250/180th bunch for 50/20 μm dusts.

Figure 5 shows the evolution per bunch passage of (a) dust charge, (b) ion charge, (c) electron charge, and (d) the number of evaporated neutral atoms. The simulation was run for 500 bunches. Electron and ion counts were truncated beyond a radius of 3 cm, while neutral atoms were truncated beyond 3 mm. Although charged particles may rapidly move away and occasionally return, neutral atoms exhibit only thermal motion and remain slow; once displaced from the beam region, they cease to affect the system. By focusing on the vicinity of the beam, the plasma state is observed to roughly saturate after ~ 300 bunches. Each bunch passage generates approximately 0.5×10^8 electrons, leading to dust charging. The dust charge reaches up to 9×10^9 in both the drift and the bend sections for $a_0 = 50 \mu\text{m}$.

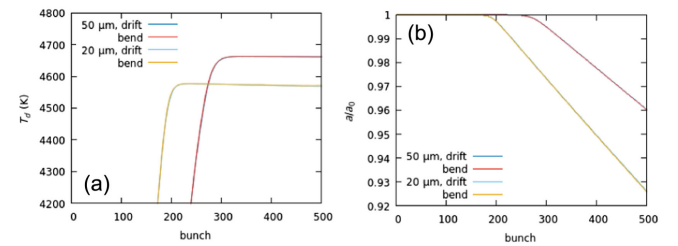


FIG. 4. Temperature rise of the dust due to beam ionization loss and the change in dust size due to evaporation. (a) Evolution of the dust temperature and (b) the change of dust size for initial radii of $a_0 = 20$ and $50 \mu\text{m}$.

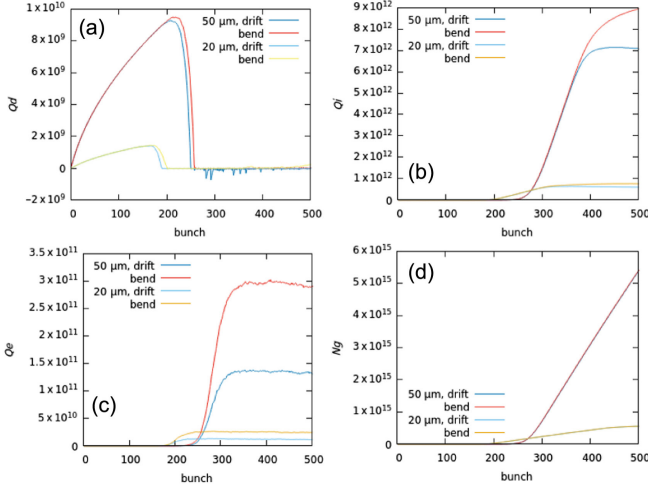


FIG. 5. Generation of dust plasma through interaction with the beam. Evolution per bunch passage of (a) dust charge, (b) ions charge, (c) electron charge, and (d) the number of evaporated neutral atoms.

After the sublimation point, evaporation becomes significant, causing a sharp decline in dust charge. This drop to $\sim 10^8$ is primarily driven by the absorption of electrons produced through beam ionization of evaporated atoms, rather than direct ionization of the evaporating material.

In the drift space, the ion and electron charges are in the range of 7×10^{12} and 1.5×10^{11} , respectively. Under a bending field, these values change to 1×10^{13} for ions and 3×10^{11} for electrons. The higher electron charge in the bend region is notable. The number of electrons is generally lower than that of ions due to their higher mobility. The number of neutral atoms increases monotonically and is saturated at > 500 th bunch due to the truncation. The values for $a_0 = 20 \mu\text{m}$ dust particle are an order of magnitude smaller.

Positrons in the bunches experience transverse kicks due to the charge distributions of the dust, ions, and electrons. While the transverse positions of the positrons remain unchanged, their transverse momenta are altered. Consequently, the bunch size remains constant, but a momentum spread develops. This effect is particularly pronounced in the vertical direction due to the smaller beam size in that plane. The change in momentum distribution subsequently induces size variations via betatron oscillation. Figure 6(a) shows the evolution of the vertical momentum spread. The momentum spread is prominent during dust interactions in both drift and bending fields. The increase in $\sigma_{py}/\sigma_{py0} > 30$ is critical for beam loss. Figures 6(b) and 6(c) display the macroparticle distributions of dust, ions, and electrons after interaction with the 500th bunch. The distributions of electrons and ions exhibit distinct features depending on the presence or absence of a bending field.

Figure 7 shows the density distribution of the dust plasma in the vicinity of the beam. The ion and electron

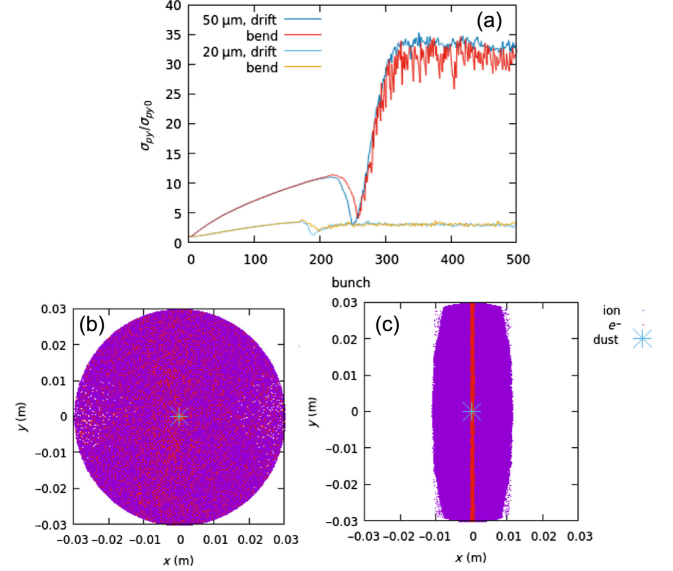


FIG. 6. Impact of beam-dust interactions on the beam and state of the dust plasma after 500 bunch passages. (a) Evolution of the vertical momentum spread during interaction with dust plasma; (b),(c) distribution of the dust plasma in drift space and bending field, respectively, where the dust is graphite with a radius of $a_0 = 50 \mu\text{m}$.

distributions represent the density during interaction with the central part of the bunch ($z = 0$). The maximum atomic gas density is $\rho_G = 1.4 \times 10^{22} \text{ m}^{-2}$, independent of whether the interaction occurs in a drift or bending section. This density is 26 times higher than that in the vacuum bump scenario ($\rho_G = 5.3 \times 10^{20} \text{ m}^{-2}$) in Sec. II. In the case of the vacuum bump, the gas is uniformly distributed, whereas here it is localized only in the vicinity of the beam. The ion and electron densities are largely independent of the field configuration, with similar maximum values of $\rho_i = 5\text{--}6 \times 10^{18} \text{ m}^{-2}$ and $\rho_e = 5\text{--}8 \times 10^{18} \text{ m}^{-2}$, respectively. It is slightly higher in the drift section. It can be inferred that the electron distribution varies during interaction along the longitudinal bunch position z , while the ion distribution remains relatively unchanged. Consequently, the integrated effect of ions is stronger than that of electrons. The observed densities are approximately 20 times higher than those resulting from ionization at the vacuum bump ($\rho_i \approx 3 \times 10^{17} \text{ m}^{-2}$), as discussed in Sec. II.

Both electrons and ions are distributed near the beam, but their densities and spatial profiles differ. Particles in the positron bunch experience a defocusing force from the ion distribution and a focusing force from the electron distribution. The net momentum kick resulting from this mixture of focusing and defocusing forces induces a transverse momentum spread σ_{py} within the bunch. Note that the beam size σ_y remains unchanged at the instant of interaction. Figure 8 shows the phase-space distribution of 500th positron bunch. Plots (a) and (b) correspond to the

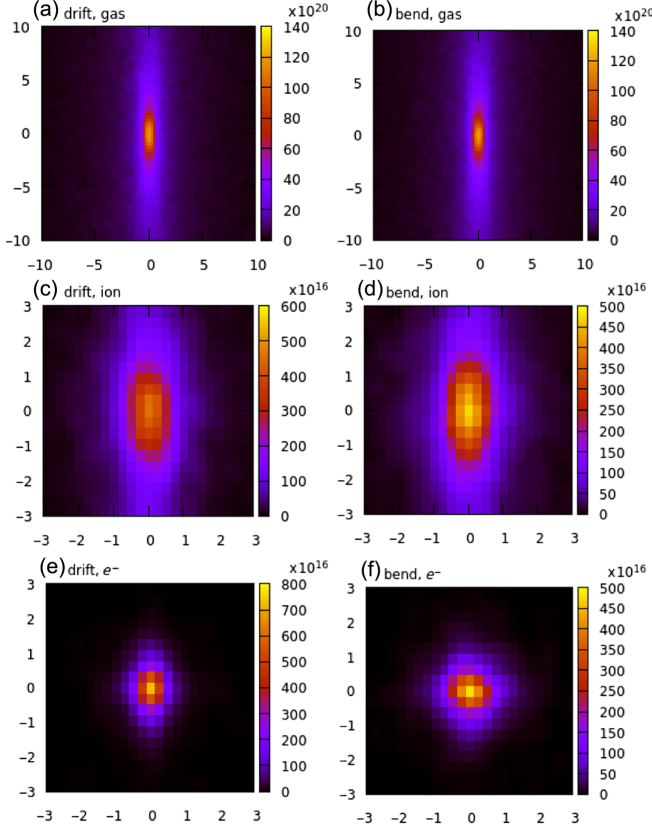


FIG. 7. Density distributions of dust plasma: (a),(b) atomic gas distributions in drift and bending fields; (c),(d) ion distributions in drift and bending fields; (e),(f) electron distributions in drift and bending fields. The color scale represents density in unit of m^{-2} . The horizontal and vertical axes represent x/σ_x and y/σ_y , respectively. Here the dust is graphite with a radius of $a_0 = 50 \mu\text{m}$.

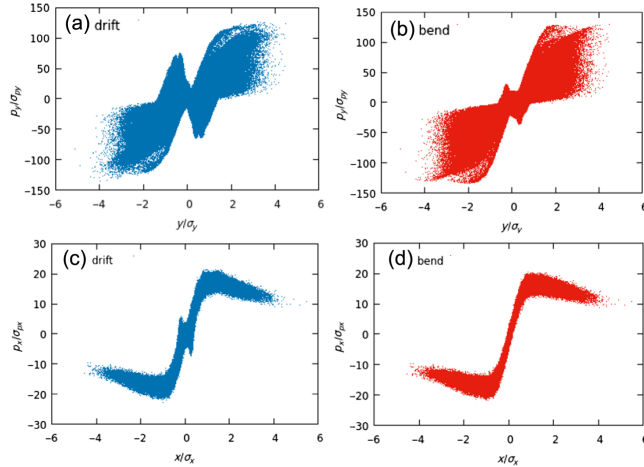


FIG. 8. Phase-space distribution of 500th bunch after interaction with dust plasma: (a) (y, p_y) plot for interaction in drift space, (b) (y, p_y) plot for interaction in a bending field, (c) (x, p_x) plot for interaction in drift space, and (d) (x, p_x) plot for interaction in a bending field. Here the dust is graphite with a radius of $a_0 = 50 \mu\text{m}$.

vertical phase-space distribution under the drift and bending field configurations, respectively. Plots (c) and (d) show the horizontal phase-space distribution. These plots exhibit predominantly defocusing forces overall, but a focusing component is also observed in regions where the amplitude is small. This behavior is consistent with the density distribution shown in Fig. 7. The vertical and horizontal distributions differ significantly. The gas distribution is approximately the same size as the beam. Ions and electrons, created within the overlap region of the beam and gas, are generated with a size smaller than that of the beam, and the horizontal size is larger than the vertical one. As a result, dp_y depends on x and exhibits significant spreading, whereas dp_x , being independent of y , shows less spreading.

Until now, ionization via beam impact and ion evaporation from charged dust have been considered. We now consider ionization by electrons within the plasma [24]. Figure 9 shows the energy distribution of electrons in the dust plasma, as derived from the data in Fig. 7. Due to acceleration by the beam, the electron energy distribution is such that approximately 40% of the electrons possess energies of 100 eV or higher. Ionization of the gas occurs due to its coexistence with these electrons within a region roughly the size of the beam. The ion production rate per bunch is given by

$$\Delta N_i = \int \rho_G(x, y) \rho_e(x, y) \sigma_i v \Delta t / l_z dx dy, \quad (16)$$

where $\rho_G = 10^{22} \text{ m}^{-2}$ and $\rho_e = 10^{19} \text{ m}^{-2}$ are the densities of gas and electrons, respectively, as shown in Fig. 7. The time during which the electron density remains high is limited to the bunch passage duration, $\Delta t = 3 \times 10^{-11} \text{ s}$. Using a cross section of $\sigma_i = 2 \times 10^{-22} \text{ m}^{-2}$, the velocity of $v_e = 10^7 \text{ m/s}$, and the longitudinal plasma extent of $l_z = 1 \text{ mm}$, the calculated ion production per bunch passage is $\Delta N_i \approx 10^{10}$. This value is comparable to the number of ions present in the beam region in Fig. 7. Taking the fields of these additionally produced electrons and ions into

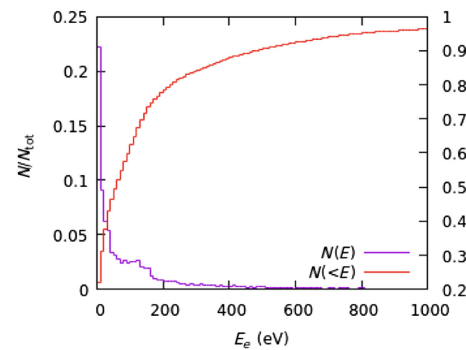


FIG. 9. Energy distribution of electrons in the dust plasma of Fig. 7.

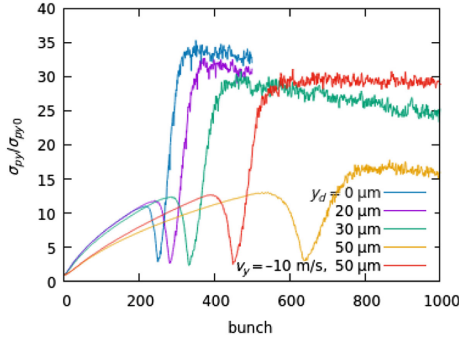


FIG. 10. Evolution of the vertical momentum spread during interaction with a dust particle located at a vertical offset from the beam center. Here the dust is graphite with a radius of $a_0 = 50 \mu\text{m}$.

account could lead to a further increase in the momentum spread of the beam.

So far, we have discussed simulations where the dust particle is placed at the center of the beam. Here, we will present a simulation where the particle is offset from the center. We computed cases where a dust particle with a radius of $a_0 = 50 \mu\text{m}$ was placed 20, 30, and 50 μm above the beam center as shown in Fig. 10. An additional case was calculated where the particle was placed 50 μm above and given an initial downward velocity of 10 m/s. For offsets of 20 and 30 μm , the momentum spread decreased by only about 10% compared to the original value. In contrast, the 50 μm offset resulted in a significant reduction of 50%. When the particle was imparted with an initial velocity of 10 m/s, it moved approximately 40 μm in 1000 bunch passages (4 μs). Due to this movement, the momentum spread returned to nearly its original value.

C. Simulation results for silicon dust

The case of a silicon dust particle is discussed at the end of this section. The interaction between a silicon dust particle and the beam was investigated in Ref. [15]. In the simulation, electrons were emitted continuously without accounting for absorption. The dust was heated and charged due to the ionization loss of beam. Since silicon liquefies at 1983 K, internal charge within the dust can cause fission. With a surface tension of silicon $\gamma_s = 10 \text{ N/m}$, the threshold of fission was calculated as $Q_{th} = 5 \times 10^8$ from Eq. (12). Since the accumulated charge substantially exceeded the threshold at the melting temperature, the dust underwent explosive fission around the 80th bunch passage. The effect on the beam became noticeable by the 200th bunch and gradually diminished with subsequent bunches.

The present model now incorporates the reabsorption of electrons returning to the dust particle, including the associated secondary electron emission. As a result, the charge on the dust does not build up to a critical explosive

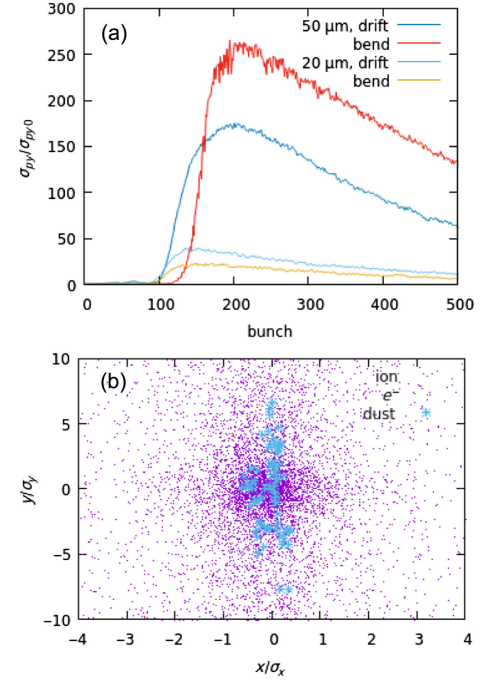


FIG. 11. Impact of beam-dust interactions on the beam and state of the dust plasma after 500 bunch passages. (a) Evolution of the vertical momentum spread during interaction with a silicon dust particle and (b) distribution of the dust plasma in drift space ($a_0 = 50 \mu\text{m}$).

level, and fission is limited to approximately 100 pieces (70 in the simulation) within the drift space. In the bending magnet, the motion of electrons is constrained, leading to their effective reabsorption. This prevents excessive charging and consequently suppresses fission.

Figure 11 shows the beam momentum spread resulting from interaction with the dust and distribution of the dust plasma in drift space. It is evident that the effect is significantly greater than for graphite, with a momentum spread 6 to 8 times larger. Even for a dust particle size of $a_0 = 20 \mu\text{m}$, it has the potential to influence beam loss. On the other hand, the momentum spread decays within approximately 300 bunches (1.2 μs) due to the processes of fission and evaporation.

V. MULTITURN SIMULATION

In SuperKEKB, each ring stores 2346 bunches. Simulating the interaction of all these bunches with dust over multiple turns is computationally difficult. Therefore, a simplified approach, described below, is adopted.

When the interaction with dust causes it to reach the sublimation point following the initial temperature rise, the resulting dust plasma interacting with the bunch reaches a steady-state distribution. As shown in Fig. 6(a), this steady state is achieved within 100 bunch passages after sublimation occurs. Although the momentum spread is observed to gradually decrease thereafter, assuming it

remains constant at a fixed value enables a simplified multiturn simulation.

The momentum change of the bunch induced by the dust plasma remains constant each time, resulting in an identical phase-space distribution. By applying the revolution matrix, the bunch distribution after one turn can be obtained. Repeating the interaction between this bunch and the dust plasma yields a new steady-state dust plasma distribution, while simultaneously producing a corresponding steady-state phase-space distribution of the bunch interacting with it. This process is iterated over multiple turns. Thus, by simulating the interaction of a single bunch with the dust plasma, it is possible to effectively model multibunch and multiturn dynamics. The beam-dust interaction over 10 turns is simulated through a total of $500 + 100 \times 10 = 1500$ times interactions, where the bunch was made to interact (with the dust) 100 times to generate a steady-state plasma distribution each revolution.

In the simulations presented in this section, to make beam loss more visible, the minimum energy deposition threshold for dust was raised from $\epsilon_{\min} = 0.7 \times 10^{-3}$ to 10 eV. As a result, the factor $\log(\epsilon_{\max}/\epsilon_{\min})$ in Eq. (6) is reduced by $\log(10/0.7 \times 10^{-3}) = 9.6$.

Figure 12 shows the turn-by-turn evolution of the beam size. The vertical and horizontal beam size and momentum spread are plotted in (a) and (b) for the drift and bending sections, respectively. The beam size in the y direction increases at the 4th and 10th turns, while the size in the x direction increases at the 8th turn. This behavior originates from the tune values of $(\nu_x, \nu_y) = (0.53, 0.57)$. At other locations in the ring, the turn at which the size becomes large varies depending on the betatron phase advance from the point of dust interaction. Considering both the beam size and momentum spread, the emittance remains nearly constant from the first interaction in both the drift and bending sections.

Figure 13 shows the particle distribution in the bunch after turns at the dust position. The distributions after the 4th and 10th turns in drift space are plotted in (a) and (b). The distributions in a bending field are plotted in (c) and (d). The distribution in the x direction exhibits a highly distinctive feature where the beam splits into two distinct

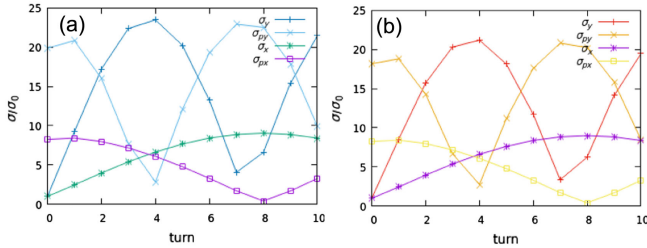


FIG. 12. Evolution of the vertical beam size and momentum spread: (a) vertical beam size and momentum spread in drift space, (b) vertical beam size and momentum spread in a bending field.

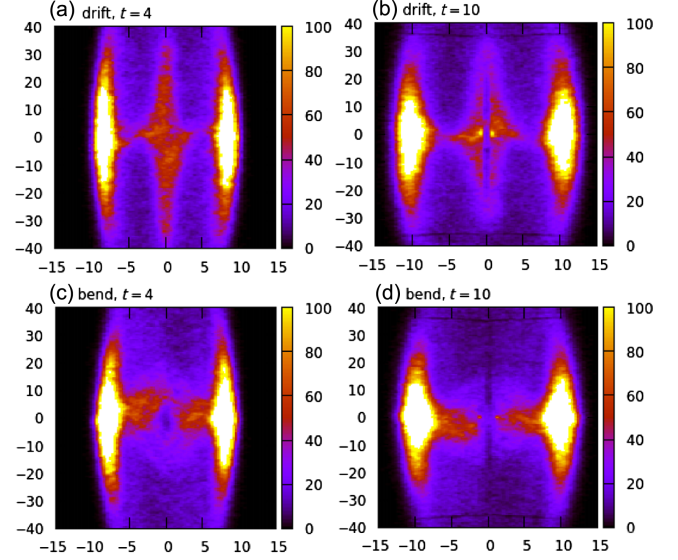


FIG. 13. Particle distribution in a bunch after dust interactions: (a) 4th turn (b) 10th turn in drift space, (c) 4th turn, (d) 10th turn in a bending field. The horizontal and vertical axes represent x/σ_x and y/σ_y . The color scale represents number distribution of macroparticles in a bunch, where the total number is 10^6 .

profiles at certain turns. This can be explained by the phase-space distribution shown in Fig. 8. Since $\sigma_x \gg \sigma_y$, there is no spread in the x phase-space distribution, and since the plasma distribution is small, even the core part of the beam experiences nonlinear kicks. Nevertheless, the key point is that the overall distribution spreads significantly in the y direction, and beam loss is ultimately determined by the vertical distribution.

The PIC grid space is set to a maximum of 40σ in the y direction, matching the aperture. Particles that exceed this grid space account for 10% in both the drift and bend sections at the 4th turn. To analyze beam loss accurately, it is necessary to track the particle distribution in phase space through the accelerator using a beam tracking code and examine the losses at the collimator. Since detailed information such as collimator settings is required, this analysis will likely be conducted separately.

VI. CONCLUSION

We have been investigating the effects of beam-dust interactions on the positron beam. Graphite and silicon particles with a diameter of 20–50 μm are assumed to be the dust. The beam loses energy due to ionization loss in the dust. The dust, in turn, loses electrons and becomes charged, while the energy received from the beam causes it to heat up, evaporate, and generate atomic gas. This gas is ionized by the beam, resulting in the formation of plasma around the beam. Unlike conventional neutral plasma, this plasma consists of dust, ions, and electrons, each with distinct charge distributions. These charge distributions exert focusing and defocusing forces on the beam,

instantaneously altering the phase-space distribution of the beam particles.

Simulations based on this scenario were conducted, tracking the distributions of dust, atomic gas, ions, and electrons after each bunch passage, and calculating the resulting momentum changes of the bunch induced by the dust plasma. Initially, simulations were performed with the dust particle placed at the beam center as the baseline condition. Subsequently, the dust position was offset from the center to investigate the effects of displacement. The results demonstrate that graphite dust with a radius of $a_0 = 50 \mu\text{m}$ and silicon dust with $\geq 20 \mu\text{m}$ induce substantial beam perturbations. They indicate that particles within the bunch can exhibit betatron amplitudes of more than $40\sigma_y$ (the aperture limit), suggesting the possibility of instantaneous beam loss. The beam perturbation scales approximately proportionally with the overlap between the dust and the beam. This concept is considered highly likely to explain the sudden beam loss (SBL) observed in SuperKEKB.

The density of the dust plasma is higher than that of the beam. As a result, the electron plasma oscillations within the dust plasma occur faster than the electron oscillations induced by the beam, making it necessary to use a finer time step and perform careful calculations for the space charge within the dust plasma. Although this paper does not address plasma oscillations inside the dust plasma, we intend to investigate them in a future study.

Similarly, the same simulation can be applied to electron beams; however, the internal state of the resulting plasma is expected to differ significantly. We intend to discuss this in a future study.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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